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FREEZING INJURY TO POTATOES

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INTRODUCTION

The annual loss from freezing while potatoes are in storage and in transit amounts to many thousands of dollars. Nearly 75 per cent of the average commercial potato crop is produced in the Northern States, where it is subject to injury by freezing from the time of harvest until the crop is finally marketed. The greater part of this quantity is produced in the States shown in Table 1.

TABLE 1.—*Potatoes produced and shipped by the six leading potato-growing States*

[From Crops and Markets (7)[1]]

State	Shipments (bushels)		Shipments (car lots)	
	1924	1925	1923	1924
Maine	44,100,000	34,170,000	34,721	43,129
Michigan	33,800,000	24,411,000	20,228	17,436
Minnesota	44,880,000	26,772,000	33,567	31,684
New York	43,400,000	23,994,000	18,522	20,133
Pennsylvania	25,370,000	25,461,000	4,095	3,948
Wisconsin	31,460,000	23,632,000	6,186	16,020

[1] Italic numbers in parentheses refer to "Literature cited," p. 23.

In some seasons, as in the fall of 1925, early freezing weather may occur before the crop is well harvested, and much injury may result to potatoes while still in the field. There is also constant danger of freezing while potatoes are in transit or in storage.

The freezing point, or the temperature at which ice formation takes place within the potato, averages about 29° F. (*6*), with varia-

tions ranging from 28.5° to 29.5° F. caused by differences in individuals, varieties, soil conditions, and seasons. Obviously, a definite figure holding under all conditions can not be stated, but the average freezing point thus given may be considered a danger point near which freezing injury is likely to occur. Within certain limits freezing injury to potatoes may or may not follow exposure to a temperature at or just below the actual freezing point, its occurrence depending upon a number of variable factors, such as the temperature of the surrounding air, the duration of exposure to low temperature, the type of package or container in which the potatoes are held, and the internal temperature of the potatoes when encountering an air temperature below the freezing point. Danger from freezing is usually less when potatoes are stored in bulk in large bins than when they are stored in sacks or barrels around which air can circulate more or less freely. Freezing will not take place until sufficient heat has been removed to bring the internal temperature of the individual potatoes to or slightly below the freezing point. While the outside of the mass is cooling, heat is constantly being transferred in decreasing measure from the interior; but since cooling is naturally more rapid near the outside, it is usually at this point that freezing injury first develops.

There is some confusion as to the proper use of the terms "frost injury," "freezing injury," and "chilling injury," which are usually used in connection with low-temperature injury to potatoes. Frost injury is properly that caused by freezing temperature to potatoes while in the field, the results being identical with those following freezing injury. Freezing injury is the term usually applied to injury caused by freezing after potatoes have been dug and removed from the field. It occurs while they are in storage or in transit. Chilling injury is a term brought into use by an apparent misconception of the effects of low temperatures. The opinion seems to persist that potatoes are definitely injured at temperatures near 32° F., the freezing point of water. Discolorations found near the stem end of some potatoes, resulting in a dark and watery product when cooked, are sometimes thought to be due to chilling. If the trouble is not due to actual freezing, which can take place only at or below the freezing point, usually it can be laid to abnormal growing conditions or unusual storage conditions. It is the consensus of opinion of investigators that injury to potatoes is not caused by low temperature alone unless actual ice formation has taken place in the tissues.

PLAN OF THE INVESTIGATIONS

It was the purpose of these investigations (1) to study the effects of various storage temperatures upon the freezing points of potatoes and their susceptibility to freezing injury, (2) to determine further the relation of undercooling to practical storage conditions, and (3) to note in detail under carefully controlled conditions the development of freezing injury as shown in the various symptoms or types of necrosis in relation to the extent or duration of exposure to definite freezing temperatures.

Three standard varieties of potatoes, viz, Irish Cobbler, Green Mountain, and Triumph, were used in these investigations. The potatoes were grown at the Aroostook farm of the Maine Agri-

cultural Experiment Station in cooperation with the United States Department of Agriculture. They were true to name and practically free from disease. The investigations were made at the cold-storage laboratory at the Arlington Experiment Farm near Rosslyn, Va., and the controlled temperatures as herein reported were obtained in different cold-storage rooms at the laboratory. All temperatures recorded are in degrees Fahrenheit.

INFLUENCE OF DIFFERENT STORAGE TEMPERATURES UPON THE FREEZING POINTS

As has been stated, the freezing point of potatoes averages about 29° F. To ascertain whether varying storage temperatures influence the freezing points of potatoes, determinations were made on lots of the three varieties mentioned after two and three months in storage at 32°, 40°, and 50°, respectively.

The freezing points recorded are the averages of determinations on 12 representative specimens of each variety. The potatoes were received from Maine on December 4 and were divided into lots and stored at 32°, 40°, and 50°. Freezing-point determinations were made on February 15 and March 16, with the results shown in Table 2.

TABLE 2.—*Average freezing points of potatoes of three varieties after two and three months in storage at stated temperatures*

Variety	Storage temperature (°F.)	Freezing points (°F.)	
		Feb. 15	Mar. 16
Irish Cobbler	32	29.10	28.82
	40	30.00	29.70
	50	30.00	30.00
Green Mountain	32	28.60	28.40
	40	29.60	29.60
	50	29.80	29.80
Triumph	32	28.86	28.60
	40	29.76	29.80
	50	29.92	30.10

It is evident from the data in Table 2 that the conditions under which the potatoes are stored will affect to some extent their freezing points, the freezing point of potatoes stored at 50° F. being practically 1 degree higher at the end of the test than that of the same variety stored at 32°. The freezing point of potatoes stored at 40° is somewhat higher than that of those stored at 32° and possibly a little lower than that of those from the 50° storage. This difference possibly can be explained in part by the variation in sugar concentration, which is always found to be greater after storage at 32° than at higher temperatures (*1*, *6*). At least the greater sugar content at 32° storage consistently correlates with a lower freezing point. Müller-Thurgau (*6*) was the first to report a lower freezing point in potatoes high in sugar concentration due to low temperature storage. From the results just reported it is reasonably safe to conclude that potatoes in storage at a temperature ranging about 32° would be more resistant to freezing injury than if held at a higher tempera-

ture, although this temperature is not recommended for potatoes held for food, because the increased sugar content at this temperature makes them rather unpalatable.

TABLE 3.—*Relation of previous storage temperatures of potatoes to susceptibility to freezing injury both when the potatoes were disturbed and when they were undisturbed*

Variety	Previous storage temperature (° F.)	Percentage of potatoes injured when exposed to 20.5° F.	
		Undisturbed potatoes	Disturbed potatoes
Irish Cobbler	32	0	65
	40	0	70
	50	30	80
Green Mountain	32	0	40
	40	0	60
	50	10	90
Triumph	32	0	50
	40	0	70
	50	40	100

Further evidence on this point was obtained from experiments conducted with potatoes from the same lots used in the former experiments. Three lots of 40 representative tubers of each variety, after three months in storage at 32°, 40°, and 50° F., respectively, were transferred to a storage room with a temperature of 20.5°, where they were spread out on a platform and allowed to remain undisturbed one and one-half hours to insure their being cooled below the freezing point. Twenty potatoes of each lot were then tossed into a basket to inoculate [1] them and to start freezing action; then they were again spread out for 45 minutes longer. The remaining 20 tubers of each lot were left undisturbed as a check. All were then removed to ordinary room temperature for three days, and were then cut and examined for evidences of freezing injury. The results (Table 3) show that the undisturbed tubers of each variety stored at 32° and 40° remained undercooled, and no freezing injury developed during the period of the experiment. Of the undisturbed tubers from storage at 50°, the proportions of the three varieties showing freezing injury were 10 per cent of the Green Mountain, 30 per cent of the Irish Cobbler, and 40 per cent of the Triumph, indicating that their resistance to freezing was less than when stored at 32° or 40°. Of those that were inoculated, the potatoes from the higher storage temperatures showed more injured individuals in all cases.

UNDERCOOLING AND RESISTANCE TO FREEZING

Earlier work in this laboratory on the undercooling of potatoes is reported in a former publication (*9*). By undercooling is meant the cooling below the freezing point without actual ice formation. Müller-Thurgau (*5*) demonstrated that plant tissue, including that

[1] "Inoculate" in the sense in which it is here used refers to the inception of freezing by mechanical means (*9*).

of the potato, might cool several degrees below the actual freezing point before ice formation took place. He reported that potatoes might undercool to temperatures ranging from 24.5° to 20.3° F. before freezing began. Later work demonstrated that the extent or duration of undercooling depends upon both external conditions and individual differences. Jarring or other disturbances may terminate the undercooling at any temperature below the freezing point. No apparent injury has been detected in numerous lots of potatoes that have been undercooled and again warmed up without actual ice formation taking place, irrespective of the temperature or

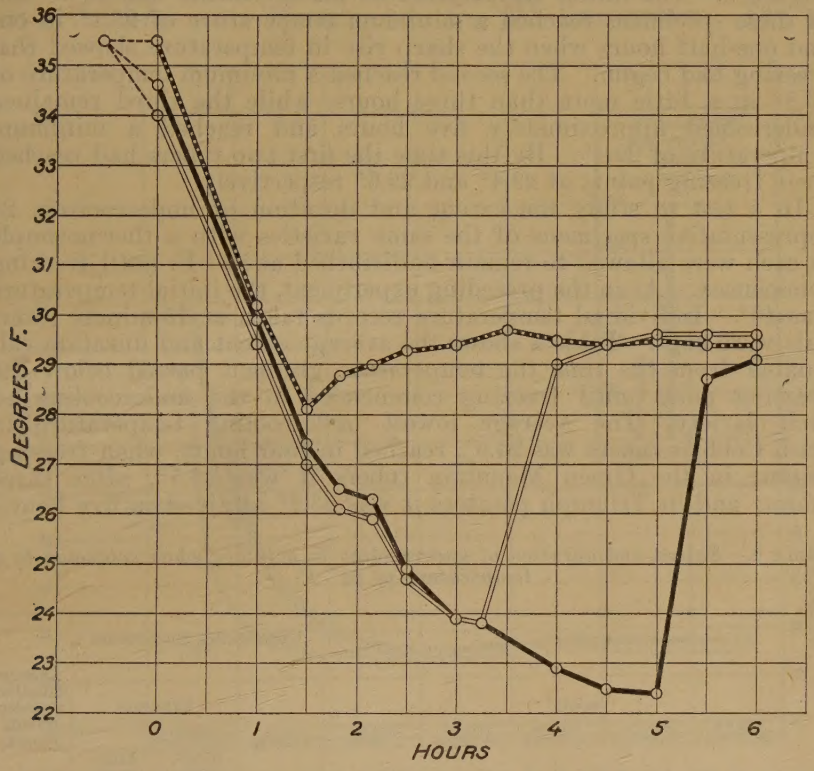


FIG. 1.—Individual variations in degree of undercooling of three Green Mountain potatoes in an air temperature of 22° F.

the extent of undercooling. Many cooking tests with potatoes which have been undercooled have failed to show any darkening or other evidence of injury. Similar results were obtained in this laboratory in a study of the apple (*2*). In one specific experiment 12 specimens of Green Mountain potatoes with a thermocouple inserted in each were placed at an air temperature of 24° and allowed to remain undisturbed for four hours. When the temperature of the potatoes had been lowered below the freezing point they were immersed in warm water to raise quickly their temperature above the freezing point. After being held at room temperature for three days, inspection showed no trace of freezing injury.

The extent to which potatoes may be undercooled under certain conditions and the varying behavior of individual tubers when subjected to a temperature below the freezing point have been demonstrated in a number of experiments and are illustrated in those herein described.

Twelve tubers of the Green Mountain variety, similar in size and appearance, with a thermocouple inserted to the center of each, were spread out on a platform and allowed to remain undisturbed at a temperature of 22° F. The temperatures were recorded every few minutes. Three of these records taken at random are shown in Figure 1. The initial temperature of all specimens was 40°. One of these specimens reached a minimum temperature of 28.1° in one and one-half hours when the sharp rise in temperature showed that freezing had begun. The second reached a minimum temperature of 23.8° in a little more than three hours, while the third remained undercooled approximately five hours and reached a minimum temperature of 22.4°. By this time the first two tubers had reached their freezing points of 29.4° and 29.6° respectively.

In a test to study the extent and duration of undercooling, 24 representative specimens of the same varieties with a thermocouple in each were allowed to remain undisturbed at 22° F. until freezing commenced. As in the preceding experiment, the initial temperature was 40°. Individual temperature records taken at 15-minute intervals were kept. Table 4 shows the average extent and duration calculated from the time the temperature gradient passed below the freezing point until freezing commenced in the undercooling of each variety. The average lowest undercooling temperature in Irish Cobbler tubers was 24.5°, reached in four hours, when freezing began; in the Green Mountain tubers it was 25.5°, after three hours; and in Triumph potatoes it was 23.2° attained in five hours.

TABLE 4.—*Extent and duration of undercooling in potatoes when subjected to a temperature of 22° F.*

Variety	Undercooling temperature (°F.)			Average duration of undercooling (hours)
	Average	Extremes		
		Maximum	Minimum	
Irish Cobbler	24.5	21.8	28.7	4
Green Mountain	25.5	22.4	28.6	3
Triumph	23.2	22.0	28.4	5

It is important to note that extreme undercooling in potatoes, as shown in the aforementioned experiments, does not usually obtain except under laboratory conditions, or where individual tubers are isolated, or at most in small containers where only a few individuals are together. Under ordinary storage conditions where potatoes are contained in bags or bins the temperature of each tuber is approximately an average of that of the surrounding individuals. The rate of cooling is much slower and, as certain results (*4*, *8*) have shown,

the ultimate undercooling point is not so low as when the rate of cooling is more rapid.

The next experiment illustrates more nearly what takes place in a bag of potatoes subjected to a temperature below the freezing point. Standard 150-pound bags of Irish Cobbler, Green Mountain, and Triumph potatoes were removed from the 40° F. storage and allowed to remain in the warmer handling room for two days. When the average temperature had reached 65° the bags were placed on their sides in a temperature of about 25°. Thermocouples were inserted in two potatoes near the bottom, middle, and top of each bag, and the recording of the temperatures was begun within half an hour after the bags were brought into the 25° temperature. The re-

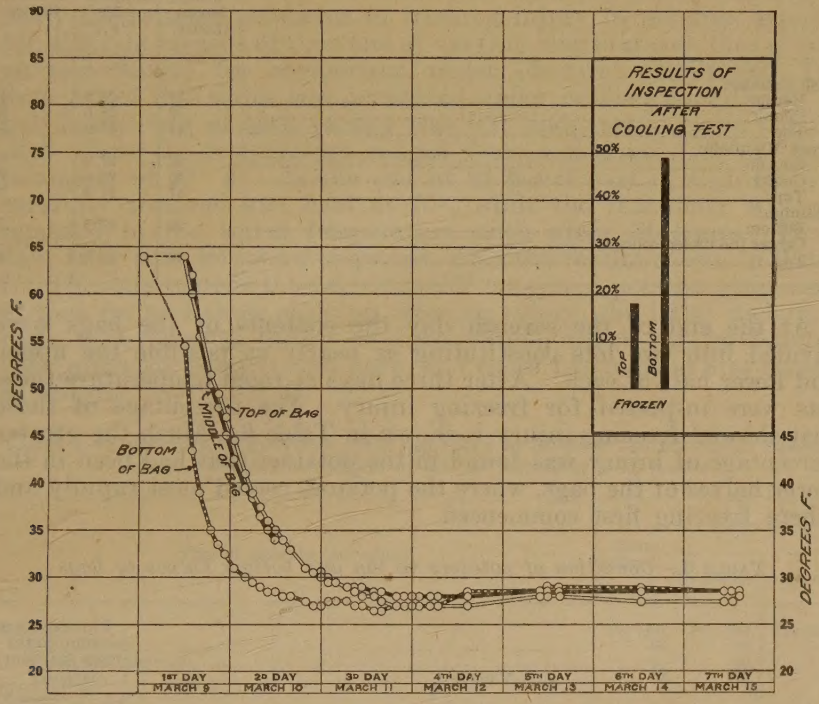


FIG. 2.—Rate of cooling of Irish Cobbler potatoes in a 150-pound bag in an air temperature of 25° F.

sults of this experiment with the Irish Cobbler potatoes are illustrated in Figure 2. Since the results obtained with the other varieties were similar, they are not shown here. From noon of the first day of the experiment temperature records were made every two hours for three days, after which less frequent readings were made, until the experiment terminated at the end of the seventh day. Figure 2 shows the average temperatures at the three positions, bottom, center, and top of the bag.

The freezing point was passed and undercooling commenced in the potatoes in the bottom of the bag within 24 hours; at the middle of the bag the freezing point was passed in 52 hours; whereas it

required 44 hours to cool those on the top to the freezing point. Table 5 shows for all three varieties the time at which undercooling began below the probable average freezing point (28.5° for the Irish Cobbler and Green Mountain varieties and 29° for Triumph). The minimum temperatures reached and the duration of undercooling before freezing commenced are also shown.

TABLE 5.—*Duration and extent of undercooling in bag lots of potatoes*

Variety and location in bag	Undercooling		
	Period after which begun (hours)	Minimum temperature (°F.)	Duration (hours)
Irish Cobbler:			
Bottom	24	26.5	42
Center	52	28.0	23
Top	44	27.0	31
Green Mountain:			
Bottom	22	27.0	10
Center	50	27.0	12
Top	47	27.5	15
Triumph:			
Bottom	20	27.5	16
Center (no undercooling)			
Top	46	27.5	20

At the end of the seventh day the contents of the bags were divided into two lots constituting as nearly as possible the upper and lower half of each. After three days at room temperature these lots were inspected for freezing injury. The percentage of those that showed freezing injury is shown in Table 6. Much the greater percentage of injury was found in the potatoes that had been in the lower halves of the bags, where the potatoes cooled most rapidly and where freezing first commenced.

TABLE 6.—*Condition of potatoes in top and bottom halves of bags*

Variety	Frozen tubers found in the bags (per cent)	
	Top half	Bottom half
Irish Cobbler	18	49
Green Mountain	21	62
Triumph	15	73

The point previously brought out and illustrated in Figure 1 that some variation exists between individual tubers in their ability or tendency to undercool apparently has some practical importance. When undercooling terminates and ice formation takes place there is a sudden rise in temperature, accompanied by a liberation of heat commonly called heat of crystallization. This is illustrated in United States Department of Agriculture Bulletin No. 916 (*9, p. 11, fig. 1*). A practical application of this phenomenon in potato stor-

ages possibly explains why "leakers," or potatoes which have been so badly frozen that the cell sap oozes out through the skin when thawed, are often found scattered here and there throughout the bins, while the surrounding potatoes are entirely unharmed. When the entire mass is cooled to a temperature below the average freezing point certain scattered individuals begin to freeze. It seems reasonable to suppose that the heat of crystallization given off by these freezing potatoes—and it has been shown that this may last for several days—serves to protect the surrounding tubers until the dangerous low-temperature period has passed. This theory in connection with the freezing of apples has already been advanced in a former bulletin (*2*).

Further experiments were conducted with the same varieties to study the relative resistance to freezing injury in potatoes exposed for different periods of time and at varying temperatures, thus giving an opportunity for comparison under identical conditions. The first test of this series was conducted under outdoor conditions. A half-bushel bag of each variety was left undisturbed in an outside shed where the temperature ranged from a maximum of 32° to a minimum of 20° F. At the end of 24 hours part of each lot was carefully removed and held at 70°, while the remainder was not removed to the warm temperature until after 72 hours. Three days later both lots were inspected, with the results shown in Table 7. The data include the percentage of uninjured potatoes remaining in each lot and those showing freezing injury, the latter including those with vascular injury or discoloration, which can be detected only when the potato is cut open, and those frozen solid and classed as leakers.

TABLE 7.—*Condition of potatoes after exposure to outdoor temperatures ranging from 32° to a minimum of 20° F. for 24 and 72 hours*

Time of exposure and variety	Uninjured	Injury found	
		Vascular	Leakers
24 hours:	*Per cent*	*Per cent*	*Per cent*
Irish Cobbler	90	10	0
Green Mountain	90	10	0
Triumph	90	10	0
72 hours:			
Irish Cobbler	56	29	15
Green Mountain	75	25	0
Triumph	50	35	15

The next test was conducted under controlled temperature conditions. Ten representative specimens of each variety were spread out, so as not to touch one another, and left undisturbed at a temperature of 22° F. for 21 hours, after which they were carefully removed to a warm room. Results of the inspection of this lot are given in Table 8. This was a rather severe test, since when spread out in this way at a room temperature as low as 22° potatoes usually reach temperatures below the freezing point in about three hours, and if disturbed injury will follow almost immediately. In this case all the uninjured tubers undoubtedly remained undercooled several hours without any freezing taking place. As in the previous

experiment, the Green Mountain variety showed less injury, 30 per cent being uninjured at the close of the experiment, as compared with 10 per cent of the Irish Cobbler and 10 per cent of the Triumph.

TABLE 8.—*Condition found in potatoes held undisturbed at 22° F. for 21 hours*

Variety	Uninjured	Vascular injury	Leakers
	Per cent	*Per cent*	*Per cent*
Irish Cobbler	10	20	70
Green Mountain	30	0	70
Triumph	10	30	60

In the next experiments larger quantities of tubers were subjected to freezing temperatures, and small lots of these were removed periodically. The three varieties were spread out at 27° F., a relatively high freezing temperature only a little below the freezing point. After 8, 24, 32, and 48 hours of exposure, lots of 20 specimens of each variety were carefully removed. The results of this experiment are shown in Table 9.

TABLE 9.—*Condition found in lots of 20 specimens of each variety of potatoes held undisturbed at 27° F. for 8 to 48 hours*

Time of exposure	Irish Cobbler			Green Mountain			Triumph		
	Uninjured	Vascular injury	Leakers	Uninjured	Vascular injury	Leakers	Uninjured	Vascular injury	Leakers
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
8 hours	100	0	0	100	0	0	100	0	0
24 hours	90	10	0	95	5	0	80	20	0
32 hours	100	0	0	95	5	0	95	5	0
48 hours	85	5	10	80	20	0	75	10	15

From Table 9 it is apparent that there was no injury after exposure for 8 hours and there was no consistent increase in injury in all varieties after exposure for 24 to 48 hours. This experiment was repeated, lots of 20 tubers being removed every eight hours beginning with the twenty-fourth hour. The results of these experiments are shown in Table 10. After 24 hours the Triumph potatoes showed 15 per cent vascular injury, while the other varieties showed none. The succeeding lots of all varieties showed a varying extent of injury, but apparently no consistent gain in the amount of injury as the length of exposure increased. It would appear that after sufficient exposure the least resistant individuals quickly succumbed, while the remainder withstood actual freezing throughout the period of the experiment.

A similar experiment was carried out at a temperature of 22° F. In this case, the temperature being so much lower than in the previous experiments, lots of 40 of each variety were removed every hour after the third through the seventh. Table 11 shows a rather consistent progressive increase in freezing injury as the period of exposure lengthened; however, the test apparently was not continued for a period sufficiently long for severe injury of the leaker type to

develop; the injury was all of the vascular type. The Triumph variety seems to be somewhat more susceptible to freezing injury under the conditions of the experiments, as indicated in Tables 8, 10, and 11.

TABLE 10.—*Condition found at 8-hour intervals in potatoes held undisturbed at 27° F. for 24 to 96 hours*

Time of exposure	Irish Cobbler			Green Mountain			Triumph		
	Uninjured	Vascular injury	Leakers	Uninjured	Vascular injury	Leakers	Uninjured	Vascular injury	Leakers
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
24 hours	100	0	0	100	0	0	85	15	0
32 hours	60	20	20	65	35	0	40	20	40
40 hours	65	30	5	65	35	0	75	20	5
48 hours	70	15	15	60	25	15	45		
56 hours	70	10	20	60	5	35	55	5	40
64 hours	35	15	50	5	10	85	30	15	55
72 hours	65	5	30	55	10	35	70	0	30
80 hours	60	5	35	55	15	30	45	0	55
88 hours	65	5	30	50	5	45	65	0	35
96 hours	75	5	20	65	0	35	35	0	65

TABLE 11.—*Condition found in potatoes held undisturbed at 22° F. for three to seven hours*

Time of exposure	Irish Cobbler			Green Mountain			Triumph		
	Uninjured	Vascular injury	Leakers	Uninjured	Vascular injury	Leakers	Uninjured	Vascular injury	Leakers
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
3 hours	95	5	0	98	2	0	98	2	0
4 hours	83	17	0	80	20	0	88	12	0
5 hours	77	23	0	85	15	0	85	15	0
6 hours	60	40	0	42	58	0	48	52	0
7 hours	45	55	0	42	58	0	35	65	0

THE DEVELOPMENT OF FREEZING INJURY

A study of the development of freezing injury in potatoes shows that freezing progresses somewhat rapidly in comparison with the rate at which it takes place in some of the fruits or other vegetables. Numerous observations on potatoes with thermocouples inserted have shown that freezing begins almost the instant undercooling terminates. When the tubers are inoculated by being struck sharply with a pencil or by quickly withdrawing and again inserting the thermocouple, freezing is indicated by a quick rise in temperature from the undercooled point to the freezing point. When apples, sweet potatoes, onions, and most other fruits and vegetables are thus treated it is usually several seconds or even minutes before freezing begins as recorded by the thermocouple. In this connection it seemed of considerable interest to determine how soon visible evidences of freezing injury would develop after freezing began.

Tests were made with the three varieties of potatoes exposed on thermocouples at a temperature of 22° F. The tubers were inoculated by quickly withdrawing and replacing the thermocouples, and

after certain periods of time had elapsed they were immersed in warm water to arrest the progress of freezing as quickly as possible. Subsequent inspections for freezing injury were made after holding the tubers for 24 hours at room temperature. In the first experiment of this series six specimens of each variety were allowed to freeze for only half a minute. When these were inspected, one specimen each of the Irish Cobbler and Green Mountain varieties showed freezing injury of slight vascular type. This experiment was repeated with 12 specimens of each variety. After one-half minute of exposure six specimens of each were removed as before, while the other six were allowed to remain for two minutes. The results given in Table 12 show that after one-half minute exposure only two Irish Cobbler potatoes showed injury. After exposure for two minutes all six of the Irish Cobbler and Green Mountain and four of the Triumph potatoes showed injury.

The experiment was again repeated, with the results shown in Table 12 (series B). This time six specimens of each variety were removed after 5, 10, 15, and 20 minutes. All six of the Irish Cobbler potatoes and five each of the other varieties showed injury after 5 minutes of freezing, and after 10 minutes all were injured; however, no specimens in this test showed other than slight vascular injury.

These experiments show that in some cases freezing injury begins to be evident in certain individuals after as short a time as half a minute of actual freezing, and after five minutes in certain experiments a large percentage of potatoes will show injury of the vascular type.

TABLE 12.—*Condition of potatoes held undisturbed at 22° F. for stated periods from half a minute to 20 minutes*

Series, variety, and time of exposure	Condition of tubers		Series, variety, and time of exposure	Condition of tubers	
	Number injured	Number uninjured		Number injured	Number uninjured
SERIES A			SERIES B		
Irish Cobbler:			Irish Cobbler:		
½ minute	2	4	5 minutes	6	0
2 minutes	6	0	10 minutes	6	0
Green Mountain:			15 minutes	6	0
½ minute	0	6	20 minutes	6	0
2 minutes	6	0	Green Mountain:		
Triumph:			5 minutes	5	1
½ minute	0	6	10 minutes	6	0
2 minutes	4	2	15 minutes	6	0
			20 minutes	6	0
			Triumph:		
			5 minutes	5	1
			10 minutes	6	0
			15 minutes	6	0
			20 minutes	6	0

The results of another experiment are shown in Table 13. Because of the large number of specimens involved in this test, thermocouples were not used as in the other experiments in this group. Potatoes of the three varieties were spread out at a temperature of 22° F., as before. After they had remained undisturbed for three hours a check lot of 10 of each variety was carefully removed to determine whether freezing had begun in any of the varieties. The remainder

of the specimens were tossed into a basket and again spread out, this operation serving as a convenient means of inoculation. At intervals of 15 and 30 minutes and 1, 2, 3, and 4 hours, 10 potatoes of each lot were removed. The longer periods of freezing were studied to determine the length of time after freezing begins when potatoes are frozen sufficiently to show the severe type of injury wherein the potatoes are frozen to death and termed "leakers" by the produce trade.

TABLE 13.—*Injured and sound potatoes after being exposed and inoculated at 22° F. for stated periods from 15 minutes to 4 hours*

Variety and time of exposure	Condition of tubers			Variety and time of exposure	Condition of tubers		
	Number uninjured	Number injured			Number uninjured	Number injured	
		Vascular injury	Soft (killed)			Vascular injury	Soft (killed)
Irish Cobbler:				Green Mountain—Con.			
Check	8	2	0	2 hours	0	9	1
15 minutes	1	9	0	3 hours	0	7	3
30 minutes	0	10	0	4 hours	0	8	2
1 hour	0	10	0	Triumph:			
2 hours	0	9	1	Check	10	0	0
3 hours	0	6	4	15 minutes	1	9	0
4 hours	0	4	6	30 minutes	0	10	0
Green Mountain:				1 hour	0	10	0
Check	10	0	0	2 hours	0	8	2
15 minutes	2	8	0	3 hours	0	4	6
30 minutes	0	10	0	4 hours	0	2	8
1 hour	0	9	1				

In Table 13 it is to be noted that none of the controls or uninoculated lots showed any injury except in the Irish Cobbler variety, 2 of the 10 specimens of which showed slight injury. This may have been caused by the potatoes being shaken or jolted while being removed from the freezing room, before the temperature of the tubers could again be raised above the freezing point. After exposure for 15 minutes practically all specimens showed some vascular injury, the more advanced types increasing as the period of freezing advanced. By the first hour in the Green Mountain variety and the second in the other varieties certain specimens showed a condition which will be called the soft type of injury; that is, the tissue had been entirely killed or frozen to death, but these tubers did not leak when thawed out. This stage precedes the leaker stage, as will be brought out in a later description of the development of the various stages of freezing injury or freezing necrosis.

From the results given in Tables 12 and 13 it is evident that under laboratory conditions—and perhaps under commercial conditions likewise—injury from freezing may occur in potatoes in as short a time as half a minute after freezing actually begins, the amount and extent of injury increasing with the length of the period of exposure. This bears out the statement of Hawkins (*3*) that "it is very doubtful * * * whether ice crystals are ever formed in the potato without injury to the tuber." He adds: "In this respect they [potatoes] are different from some of the other vegetables and fruits."

TYPES OF INJURY FROM FREEZING

Jones, Miller, and Bailey (4) have described fully the principal types of freezing necrosis as (1) the net type, showing "more or less general blackening of the finer ramifications of the vascular elements extending as a network from the vascular ring internally toward the pith"; (2) the ring type, "characterized by a more pronounced blackening of the tissues in and adjacent to the vascular ring. It may be rather wide and diffuse or narrow and intensely blackened and is often restricted to the stem end"; (3) the blotch type, which "constitutes a less well-defined type where the discoloration appears as small ovoidal or larger irregular patches ranging from an opaque grayish color to sooty black. These occur most commonly in the vascular ring and cortex, although they may be located in the pith." They state that these three types of injury are not evident unless the potato is cut. Freezing injury of the vascular type reduces the salability of potatoes, since it renders them unattractive when prepared for the table; however, those with the milder forms of vascular injury are practically as palatable as uninjured potatoes.

The final stage of freezing injury is commonly called the leaker stage, in which the potato tissue has become so injured by freezing that on thawing the cell sap oozes out through the skin, leaving a soft, wet product that soon begins to decay. Still another type of injury just precedes the leaker stage, that in which the tuber is killed but does not immediately collapse and break down in thawing, a condition which is quite distinct from those described by the aforementioned writers. Potatoes in this condition do not show injury on the surface for a few days unless kept in a warm place, but since the cells have been killed, decomposition (usually bacterial) eventually sets in and produces a spongy, "cheesy," and foul-smelling mass. Before decomposition occurs potatoes of this type appear to be perfect, but they lack the crackle or snap of normal tubers when cut and have a characteristic sour smell.

In advanced stages of the blotch type many of the potatoes may be so severely frozen as to be killed, and such portions of the tuber may break down through decomposition after four or five days at a temperature around 70° F. Sometimes under ordinary storage conditions specimens of all the types of necrosis are found in the same lot. This is undoubtedly explained by the fact that different tubers will undercool to different temperatures and that the duration of the period of undercooling depends, partly at least, upon individual variations in the tubers themselves. Therefore, under ordinary storage conditions where the temperature has been allowed to go below the freezing point, certain individuals may remain undercooled while others begin to freeze, with the result that various stages of freezing necrosis will be found in potatoes exposed to the same temperature for the same period of time.

Under carefully controlled laboratory conditions an effort was made to ascertain the correlation existing between the time of exposure of potatoes to freezing conditions and the resultant type of freezing necrosis. In these tests, to make certain that all the potatoes were of uniform temperature and had begun to freeze at the same time, they were spread out in a single layer on a wooden platform in a freezing room for a definite period of time. They were

inoculated by tossing them into a basket as quickly as possible in such a way as to jolt them sharply without bruising, after which they were again spread on the platform. The first group of experiments was conducted at a temperature of 26° F., at which point it was found necessary to leave the potatoes for about 18 hours, usually over night, before inoculation, in order that they might be sufficiently undercooled to start freezing promptly. A comparable group of experiments was conducted at a temperature varying between 21° and 22°, at which an exposure for three to four hours was sufficient to undercool the potatoes uniformly. Under these conditions most of the tubers in any one experiment began to freeze at practically the same time, although in some cases, particularly at the 26° temperature, a few isolated specimens were more resistant and remained uninjured for some time. On the other hand, a few individuals were found which had begun to freeze in the check lots which were removed as carefully as possible just before the other lots were inoculated. However, a sufficient number of specimens were used in these experiments so that these irregularities do not materially affect the average.

TABLE 14.—*Types of freezing injury found in potatoes exposed at 26° F. for stated periods after inoculation, then held at room temperature, and inspected after 48 hours*

Variety and time of exposure after inoculation	Type of injury											
	Experiment A						Experiment B					
	No injury	Net	Ring	Blotch	Soft	Leaker	No injury	Net	Ring	Blotch	Soft	Leaker
Irish Cobbler:	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
Check	100	0	0	0	0	0	65	0	35	0	0	0
½ hour	45	10	40	5	0	0	0	0	10	85	5	0
1 hour	20	25	10	45	0	0	0	25	10	35	15	15
2 hours	0	0	40	60	0	0	0	35	5	60	0	0
3 hours	0	0	0	100	0	0	0	30	0	60	5	5
4 hours	0	0	0	100	0	0	0	5	0	65	30	0
5 hours	0	0	0	100	0	0	0	10	0	70	20	0
Green Mountain:												
Check	100	0	0	0	0	0	100	0	0	0	0	0
½ hour	85	0	15	0	0	0	70	10	0	10	10	0
1 hour	50	0	25	25	0	0	40	10	0	40	10	0
2 hours	30	0	0	70	0	0	35	0	0	30	35	0
3 hours	15	0	0	80	0	5	0	0	0	65	10	20
4 hours	5	0	5	90	0	0	0	0	0	60	30	10
5 hours	5	0	0	85	5	5	0	0	0	85	15	5
Triumph:												
Check	100	0	0	0	0	0	95	0	5	0	0	0
½ hour	90	0	10	0	0	0	50	5	15	0	30	0
1 hour	40	0	20	40	0	0	15	0	30	25	30	0
2 hours	25	0	0	75	0	0	5	0	10	40	35	10
3 hours	20	0	5	75	0	0	0	0	0	40	50	10
4 hours	0	0	10	65	25	0	0	0	0	30	65	5
5 hours	0	0	0	65	35	0	0	0	0	45	55	0

At the 26° F. temperature two rather comprehensive experiments were conducted with the three varieties of potatoes, in which inoculated lots of 20 of each variety were removed after half an hour, 1, 2, 3, 4, and 5 hours, respectively. At the end of 48 hours at room temperature inspections were made and the types of injury recorded.

The results are shown in Table 14. The types of injury as given are necessarily arbitrary because of overlapping types, but all specimens were classified according to the seemingly predominating type. Owing probably to the comparatively high freezing temperature in these experiments, a large percentage of potatoes of all varieties showed more or less resistance to freezing injury, even after being inoculated. In this connection, from a study of the column headed "No injury," it will be seen that the Irish Cobbler potatoes were the least resistant, while Green Mountain potatoes were most resistant.

From these results it would seem that either the net or the ring type of injury is prevalent in the earlier stages of freezing injury, while other types of injury become more common as the length of time increases during which the potatoes are exposed to freezing temperatures. Net necrosis appeared only in Irish Cobbler potatoes in experiment A (Table 14), while in experiment B this type of injury was found in all the varieties but was most prevalent among the Irish Cobbler potatoes. Ring necrosis was evident in the early stages of freezing in both experiments but did not appear in the Green Mountain variety in experiment B. They showed less ring necrosis than the other two varieties, while the Irish Cobbler potatoes showed more. In experiment A it is shown that the blotch type of injury increased rather consistently as the time of exposure to the low temperatures was lengthened, while in the tubers exposed for the longer periods the soft and leaker types of injury were rather common in Green Mountain and Triumph potatoes. Where the injury was more severe, as reported in experiment B, considerable blotch and soft types of injury were apparent in the early stages of exposure, without any consistent increase as the exposures lengthened. The number of leakers did not definitely increase with the lengthening of the period of exposure.

The next group of experiments consisted of studies of the various types of freezing injury, conducted at a freezing temperature of 22° F., with shorter exposures after inoculation varying from half a minute to five hours. In the first group of tests, owing to the very short periods of exposure, a thermocouple was used in each potato to make sure of prompt freezing following inoculation. These tests included exposures for periods from half a minute to 20 minutes. The potatoes, after the desired time interval had elapsed, were inoculated by quickly removing and reinserting the thermocouples, and six specimens were removed at the end of each period. The results are shown in Table 15. After exposure of half a minute two Irish Cobbler potatoes showed injury, one net and one ring necrosis. After exposures for less than 15 minutes the numbers of tubers showing the net and ring types of injury were nearly equal. After exposure for the full 15 minutes all six specimens showed ring necrosis, and all those removed after 20 minutes showed blotch necrosis. Potatoes of the Green Mountain variety showed no injury after a half-minute exposure, while the ring type of injury predominated throughout the experiment regardless of the lengths of exposure. The Triumph variety showed no injury after half a minute and only the ring type of injury up to the end of the experiment.

TABLE 15.—*Types of freezing injury found in potatoes exposed at 22° F. for half a minute to 20 minutes after inoculation*

Variety and time of exposure	Number of tubers representing each type					
	No injury	Net	Ring	Blotch	Soft	Leaker
Irish Cobbler:						
½ minute	4	1	1	0	0	0
2 minutes	0	1	5	0	0	0
5 minutes	0	6	0	0	0	0
10 minutes	0	2	4	0	0	0
15 minutes	0	0	6	0	0	0
20 minutes	0	0	0	6	0	0
Green Mountain:						
½ minute	6	0	0	0	0	0
2 minutes	6	0	0	0	0	0
5 minutes	1	0	5	0	0	0
10 minutes	0	1	5	0	0	0
15 minutes	0	3	3	0	0	0
20 minutes	0	0	6	0	0	0
Triumph:						
½ minute	6	0	0	0	0	0
2 minutes	2	0	4	0	0	0
5 minutes	1	0	5	0	0	0
10 minutes	0	0	6	0	0	0
15 minutes	0	0	6	0	0	0
20 minutes	0	0	6	0	0	0

In the next set of experiments the three varieties of potatoes were undercooled for three hours. After check lots of 20 tubers of each variety had been removed the remaining tubers were inoculated, and thereafter lots of 20 were removed after 15 minutes, half an hour, 1, 2, 3, and 4 hours, respectively. After 48 hours at room temperature, one-half of each lot was inspected, while the remainder of the tubers were held for 192 hours before they were inspected, to determine any appreciable progressive change in the types of injury following exposure.

The results with Irish Cobblers are shown in Table 16. On the first inspection, made 48 hours after exposure, 20 per cent of the check lot showed ring necrosis, while in the other lots this type of injury seemed to predominate over the net type. The second inspection, made after 192 hours of exposure, showed 30 per cent of the check lots with net necrosis, and this type also predominated in the other lots.

The greatest amount of blotch type of injury was found in potatoes which had been exposed to freezing temperature for half an hour and one hour and then were inspected after being held 48 hours at room temperature. In both cases the number of specimens showing the blotch type of injury diminished as the period of exposure lengthened, while the number of specimens showing the soft type of injury increased.

In the Green Mountain variety (Table 16) the check lot showed no injury on the first inspection, after 48 hours in the warm room, and 10 per cent on the second inspection after 192 hours. The ring type of injury predominated in the early stages of exposure but was found to a less extent after the first inspection, having apparently developed into blotch. Netting was found in only one lot, and this occurred after half an hour of freezing and was apparent only on

the second inspection. In general, blotch was found to a greater extent on the second inspection.

With Triumph potatoes (Table 16), the checks showed no injury. Netting was found only after a quarter of an hour of freezing on the first inspection. As with Green Mountain potatoes, ring necrosis was found to a less extent on the second inspection, whereas blotch was found to a somewhat greater extent. With all varieties the ring and blotch types diminished and the soft type increased as the duration of the exposures was prolonged. Changes were noted in the type of injury between the first and the second inspection.

TABLE 16.—*Types of freezing injury found in potatoes exposed at 22° F. for stated periods after inoculation, then held at room temperature, and inspected after 48 and 192 hours*

Variety and time of exposure	Type of injury											
	First inspection, after 48 hours						Second inspection, after 192 hours					
	No injury	Net	Ring	Blotch	Soft	Leaker	No injury	Net	Ring	Blotch	Soft	Leaker
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Irish Cobbler:												
Check	80	0	20	0	0	0	70	30	0	0	0	0
¼ hour	10	30	50	10	0	0	10	20	0	70	0	0
½ hour	0	20	0	80	0	0	0	40	0	60	0	0
1 hour	0	0	0	90	10	0	0	30	0	60	10	0
2 hours	0	0	40	50	10	0	0	0	0	50	50	0
3 hours	0	0	30	30	40	0	0	0	0	0	100	0
4 hours	0	0	0	40	60	0	0	0	0	0	100	0
Green Mountain:												
Check	100	0	0	0	0	0	90	0	10	0	0	0
¼ hour	20	0	80	0	0	0	50	0	20	30	0	0
½ hour	0	0	80	20	0	0	0	40	10	50	0	0
1 hour	0	0	40	50	10	0	0	0	0	90	10	0
2 hours	0	0	0	90	10	0	0	0	0	90	10	0
3 hours	0	0	0	70	30	0	0	0	0	50	50	0
4 hours	0	0	0	0	100	0	0	0	0	0	100	0
Triumph:												
Check	100	0	0	0	0	0	100	0	0	0	0	0
¼ hour	10	20	70	0	0	0	0	0	60	40	0	0
½ hour	0	0	70	30	0	0	0	0	10	90	0	0
1 hour	0	0	20	80	0	0	0	0	10	90	0	0
2 hours	0	0	10	70	20	0	0	0	0	80	20	0
3 hours	0	0	0	40	60	0	0	0	0	40	60	0
4 hours	0	0	0	20	80	0	0	0	0	0	100	0

In the next set of experiments lots were removed after half an hour, 1 hour, and 2, 3, 4, and 5 hours of exposure, and inspections were made after 48 and 72 hours. In the previous experiment, where the second inspection was made after 192 hours, it was particularly difficult to separate the blotch and soft types of injury, as decay in most instances had set in and the soft-type potatoes had become so discolored as to make them almost indistinguishable from the blotch-type potatoes.

Results for the Irish Cobbler variety (Table 17) show no injury in the checks on the first inspection after 48 hours following exposure, but on the second inspection 30 per cent had netting after 72 hours. After half an hour of exposure 20 per cent showed netting on the second inspection. No other instance of netting was present. Ring

necrosis was most prevalent in the early stages of exposure at the 48-hour inspection. Blotch was found most prevalent at the second inspection; the ring type had apparently advanced into this classification. In Green Mountain potatoes (Table 17) the checks showed no injury. Netting was found only at the second inspection after half an hour of freezing. With Triumph potatoes (Table 17) no injury was found in the checks, and with the various exposures no netting was found. The other types of injury noted in connection with Irish Cobbler potatoes will apply very largely to both the Green Mountain and the Triumph varieties.

TABLE 17.—*Types of freezing injury found in potatoes exposed at 22° F. for stated periods after inoculation, then held at room temperature, and inspected after 48 and 72 hours*

Variety and time of exposure	Type of injury											
	First inspection, after 48 hours						Second inspection, after 72 hours					
	No injury	Net	Ring	Blotch	Soft	Leaker	No injury	Net	Ring	Blotch	Soft	Leaker
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Irish Cobbler:												
Check	100	0	0	0	0	0	70	30	0	0	0	0
½ hour	20	0	40	40	0	0	20	20	10	50	0	0
1 hour	30	0	10	60	0	0	0	0	0	100	0	0
2 hours	0	0	10	90	0	0	0	0	0	100	0	0
3 hours	0	0	0	80	20	0	0	0	0	70	30	0
4 hours	0	0	0	30	70	0	0	0	0	50	50	0
5 hours	0	0	0	40	60	0	0	0	0	30	70	0
Green Mountain:												
Check	100	0	0	0	0	0	100	0	0	0	0	0
½ hour	30	0	20	50	0	0	20	20	0	60	0	0
1 hour	20	0	10	70	0	0	0	0	0	100	0	0
2 hours	0	0	50	40	10	0	0	0	0	80	20	0
3 hours	0	0	0	90	10	0	0	0	0	70	30	0
4 hours	0	0	0	50	50	0	0	0	0	50	50	0
5 hours	0	0	0	40	60	0	0	0	0	10	90	0
Triumph:												
Check	100	0	0	0	0	0	100	0	0	0	0	0
½ hour	30	0	70	0	0	0	30	0	40	30	0	0
1 hour	10	0	90	0	0	0	0	0	20	80	0	0
2 hours	0	0	0	100	0	0	0	0	10	90	0	0
3 hours	0	0	0	60	40	0	0	0	0	100	0	0
4 hours	0	0	0	30	70	0	0	0	0	100	0	0
5 hours	0	0	0	10	90	0	0	0	0	0	50	50

A further study of the change in types of freezing injury during subsequent storage was made in which lots of each variety were frozen for one hour after inoculation at a temperature of 22° F. An inspection was made of 20 of each variety after 48 hours at 40° storage and again after five months at the same storage temperature. The results are shown in Table 18. After five months in storage at 40° no considerable change was to be noted. Perhaps in some instances during these experiments certain differences in diagnoses were due more to the personal equation than to actual changes in the potatoes, because of the difficulty of classifying the overlapping symptoms. However, evidence does seem to show that there is some change in the symptoms of freezing injury, especially during the first four or five days after removal to a warm temperature.

TABLE 18.—*Types of freezing injury found in potatoes exposed to freezing at 22° F. for one hour, then stored at 40° F., and inspected after periods of 48 hours and five months*

Storage period and variety	Type of injury					
	No injury	Net	Ring	Blotch	Soft	Leaker
48 hours:	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Irish Cobbler	0	0	0	100	0	0
Green Mountain	0	40	20	40	0	0
Triumph	0	0	0	100	0	0
5 months:						
Irish Cobbler	0	0	15	85	0	0
Green Mountain	0	50	0	50	0	0
Triumph	0	0	0	100	0	0

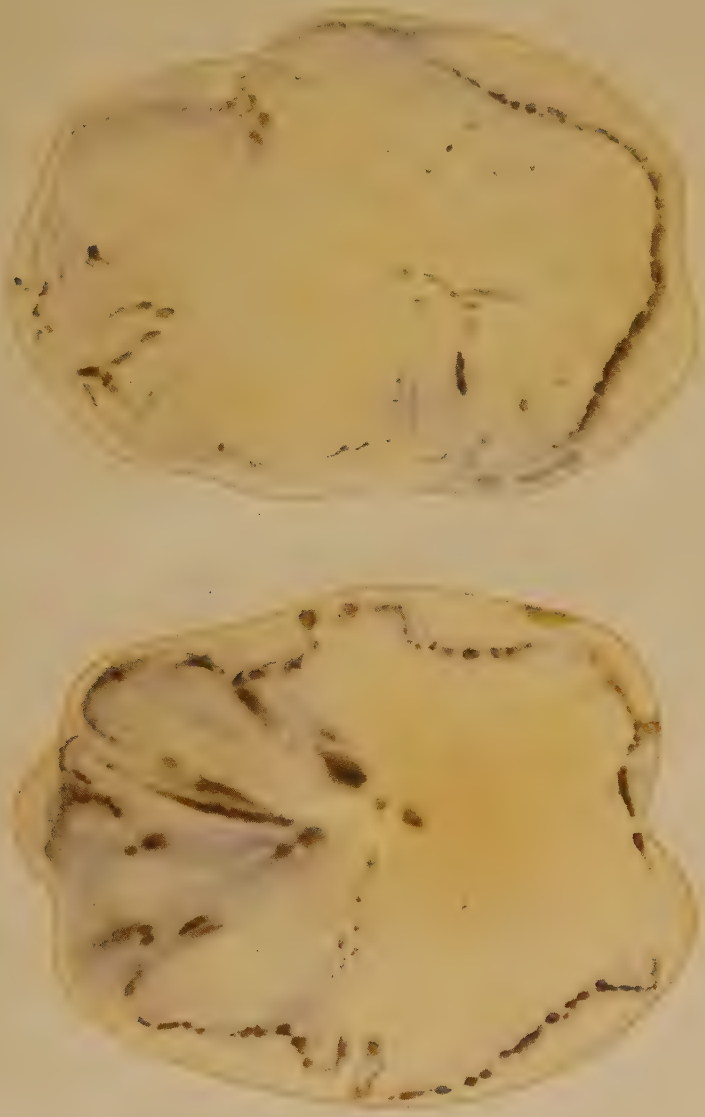
Further tests were made to study the types of freezing injury in potatoes stored at different temperatures following freezing. In the first group potatoes of the three varieties were frozen half an hour, 1 hour, 2 and 3 hours, then part were stored at 40° F. and part at 70° F. Inspections were made on lots of 20 each after 2 days, and again after 16 days. The results are shown in Table 19. Check lots not inoculated were also included, but since these did not show injury they are not shown in the table. The period of exposure was apparently not long enough to produce injury of the leaker type. The results of these tests as a whole show no marked differences in the results of tests in which storage at 40° and 70° followed freezing exposure. Most of the differences are found in the lots frozen for half an hour, and most of these differences are probably due to error in diagnosis. Some differences are also noted in the 70° storage between the lots inspected after 2 days and those inspected after 16 days. At this higher temperature some breakdown is to be expected, and this is shown as decay after 16 days in storage.

As heretofore stated, it is difficult to tabulate the results of the freezing tests, because of the overlapping of the various types of injury. As a general conclusion from these studies of the types of freezing injury it seems apparent that under given conditions, where the exposure has been comparatively light, the first stages of freezing injury are either the net and ring types or both together, as shown in Plate 1. As the freezing process advances the blotch type is more in evidence, as seen in Plate 2. After longer exposure often the extent and intensity of vascular discoloration lessens, and potatoes in this condition are found showing only a few scattered dots, usually near the cortex (pl. 3). Potatoes with blotch injury, if left under conditions favorable for germination, will usually be found with only a few eyes alive. In cases of more severe freezing injury all trace of vascular discoloration disappears (pl. 3). If examined within a few hours after exposure, the tubers have the appearance of normal specimens, but with a somewhat "cheesy" texture and sour odor when cut open, and when exposed to ordinary room temperature for from 12 to 24 hours they usually develop a reddish brown marbled appearance. With more severe exposure this soft stage develops into the leaker stage, when freezing is so far advanced that the sap escapes from the potato as soon as thawed. Leakers show no discoloration when cut

H. C. Steadman.

IRISH COBBLER POTATOES FROZEN FOR 5 MINUTES (UPPER), SHOWING FAINT RING NECROSIS, AND FOR 20 MINUTES (LOWER), SHOWING RING AND NET NECROSIS

The exact inception of freezing was determined by means of a thermocouple inserted to the center of each specimen



H. C. Steadman.

IRISH COBBLER POTATOES FROZEN FOR ONE HOUR (UPPER), SHOWING HEAVY RING NECROSIS, AND FOR THREE HOURS (LOWER), SHOWING RING AND BLOTCH NECROSIS

R. C. Steadman.

IRISH COBBLER POTATOES FROZEN FOR FOUR HOURS (UPPER), SHOWING A MARKED DISAPPEARANCE OF TYPICAL NECROSIS, AND FOR FIVE HOURS (LOWER), SHOWING AN ABSENCE OF TYPICAL NECROSIS

Although the appearance is much the same as that of an uninjured potato, the texture was cheeselike and there was a faint sour odor

open, but a pink color, which later changes to brown and then black, soon develops on the cut surface.

TABLE 19.—*Types of freezing injury found in potatoes exposed to freezing for stated periods, then stored at 40° and 70° F., and inspected after 2 days and 16 days*

Storage temperature and period of exposure	Type of injury																	
	Irish Cobbler						Green Mountain						Triumph					
	No injury	Net	Ring	Blotch	Soft	Decayed	No injury	Net	Ring	Blotch	Soft	Decayed	No injury	Net	Ring	Blotch	Soft	Decayed
	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.
40° F. after 2 days:																		
½ hour	10	45	9	35	0	0	25	0	50	25	0	0						
1 hour	5	10	0	85	0	0	10	0	25	65	0	0	0	0	40	60	0	0
2 hours	0	0	0	75	25	0	0	0	15	75	10	0	0	0	50	40	10	0
3 hours	0	0	0	70	30	0	0	0	0	65	35	0	0	0	20	45	35	0
40° F. after 16 days:																		
½ hour	30	10	0	60	0	0	0	0	60	40	0	0						
1 hour	5	5	0	90	0	0	0	0	20	80	0	0	0	0	45	55	0	0
2 hours	0	0	0	75	25	0	0	0	0	90	10	0	0	0	0	100	0	0
3 hours	0	0	0	70	30	0	0	0	0	60	35	5	0	0	0	65	25	10
70° F. after 2 days:																		
½ hour	0	100	0	0	0	0	0	0	50	50	0	0						
1 hour	0	0	0	100	0	0	0	0	40	60	0	0	0	5	90	5	0	0
2 hours	0	0	0	75	25	0	0	0	0	100	0	0	0	0	35	50	15	0
3 hours	0	0	0	25	75	0	0	0	0	85	15	0	0	0	20	70	10	0
70° F. after 16 days:																		
½ hour	20	0	0	80	0	0	0	0	0	100	0	0						
1 hour	0	5	0	95	0	0	0	0	0	100	0	0	0	0	100	0	0	0
2 hours	0	0	0	75	0	25	0	0	0	100	0	0	0	0	15	50	30	5
3 hours	0	0	0	25	0	75	0	0	0	60	0	40	0	0	0	70	0	30

SUMMARY

The average freezing point of potatoes of the standard commercial varieties is about 29° F. The point is not fixed, but may vary with the individual tuber. For practical purposes 29° should be considered a danger point near which freezing injury is likely to occur. Whether freezing injury occurs at an exposure below this temperature depends, among other factors, on the type of container, the duration of exposure, and the internal temperature of the tubers immediately before the exposure.

The freezing point of potatoes varies somewhat with the temperature at which they have been stored. The average freezing points of potatoes of three varieties were found to be practically 1 degree lower when stored for several weeks at 32° than when stored at 50° F. Also potatoes from 32° storage showed less freezing injury than those from 50° after all were exposed to the same freezing temperature.

Under certain conditions potatoes can be undercooled to several degrees below their freezing points without freezing or other injury taking place.

Individual variations in the ability of potatoes to undercool when exposed to freezing temperatures probably account for the presence of certain frozen potatoes often found scattered among uninjured ones in storage.

Freezing injury was apparent in certain potatoes after only half a minute of freezing. The extent and character of injury increased with the time of exposure after freezing commenced.

Either net or ring type of necrosis occurred in the earlier stages of injury. With greater exposure a more pronounced ring type of necrosis blended into the blotch type. With more extreme exposure the marked blackening of the vascular areas disappeared, and instead the tubers were distinguished by a characteristic cheeselike texture and chalky appearance. This stage preceded the leaker stage in which the surface of tubers become wet on thawing out.

LITERATURE CITED

(1) APPLEMAN, C. O.
1912. CHANGES IN IRISH POTATOES DURING STORAGE. Md. Agr. Expt. [illegible] 167, p. 327–334.

(2) DIEHL, H. C., and WRIGHT, R. C.
1925. FREEZING INJURY OF APPLES. Jour. Agr. Research 29: 99–127, illu[illegible]

(3) HAWKINS, L. A.
1922. THE EFFECT OF LOW TEMPERATURE STORAGE AND FREEZING ON FRUITS AND VEGETABLES. Amer. Jour. Bot. 9: 551–556.

(4) JONES, L. R., MILLER, M., and BAILEY, E.
1919. FROST NECROSIS OF POTATO TUBERS. Wis. Agr. Expt. Sta. Research Bul. 46, 46 p., illus.

(5) MÜLLER, H., *Thurgau.*
1880–1886. ÜBER DAS GEFRIEREN UND ERFRIEREN DER PFLANZEN. Landw. Jahrb. 9: 133–189, 1880; 15: 453–610, 1886.

(6) ———
1882. UEBER ZUCKERANHÄUFUNG IN PFLANZENTHEILEN IN FOLGE NIEDERER TEMPERATUR. Landw. Jahrb. 11: 751–828, illus.

(7) UNITED STATES DEPARTMENT OF AGRICULTURE. BUREAU OF AGRICULTURAL ECONOMICS.
1925. STATISTICS OF IMPORTANT CROPS, BY STATES, 1924 AND 1925. POTATOES. U. S. Dept. Agr. Crops and Markets, Mo. Sup. 2: 386.

(8) WRIGHT, R. C., and HARVEY, R. B.
1921. THE FREEZING POINT OF POTATOES AS DETERMINED BY THE THERMOELECTRIC METHOD. U. S. Dept. Agr. Bul. 895, 7 p., illus.

(9) ——— and TAYLOR, G. F.
1921. FREEZING INJURY TO POTATOES WHEN UNDERCOOLED. U. S. Dept. Agr. Bul. 916, 15 p., illus.

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